

Cryogenic Test Results of Hextek Mirror

James B. Hadaway

The University of Alabama in Huntsville

Phil Stahl, Ron Eng, & Bill Hogue

Marshall Space Flight Center

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Introduction

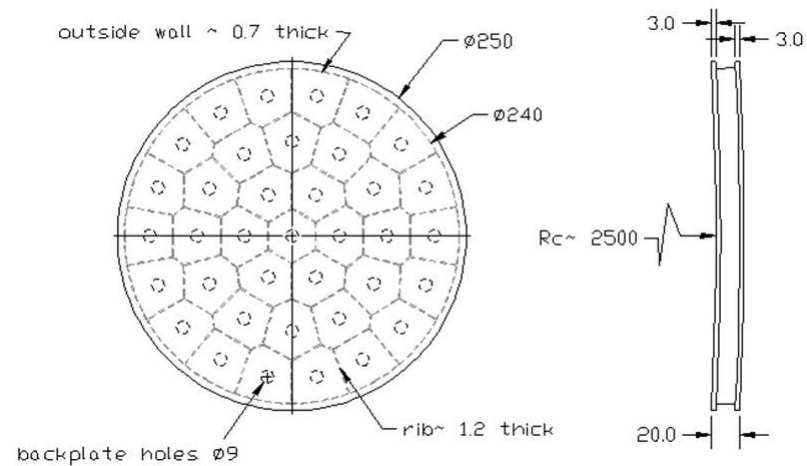


- Will describe results of two separate cryo-tests of the 0.25m borosilicate mirror manufactured by Hextek Corporation and polished by MSFC-SOMTC.
- *First cryo-test* in December of 2003 to measure surface figure change from ambient (~290K) to cryo (~30K) and repeatability of change.
- *Second cryo-test* in April & May of 2004 to assess effectiveness of single cryo-null figuring run made by QED Technologies, Inc. using MRF and to measure RoC change from ambient to cryo.

Test Mirror



See optics.nasa.gov (Tech Days pages) for Hextek papers with more info on design & manufacture.



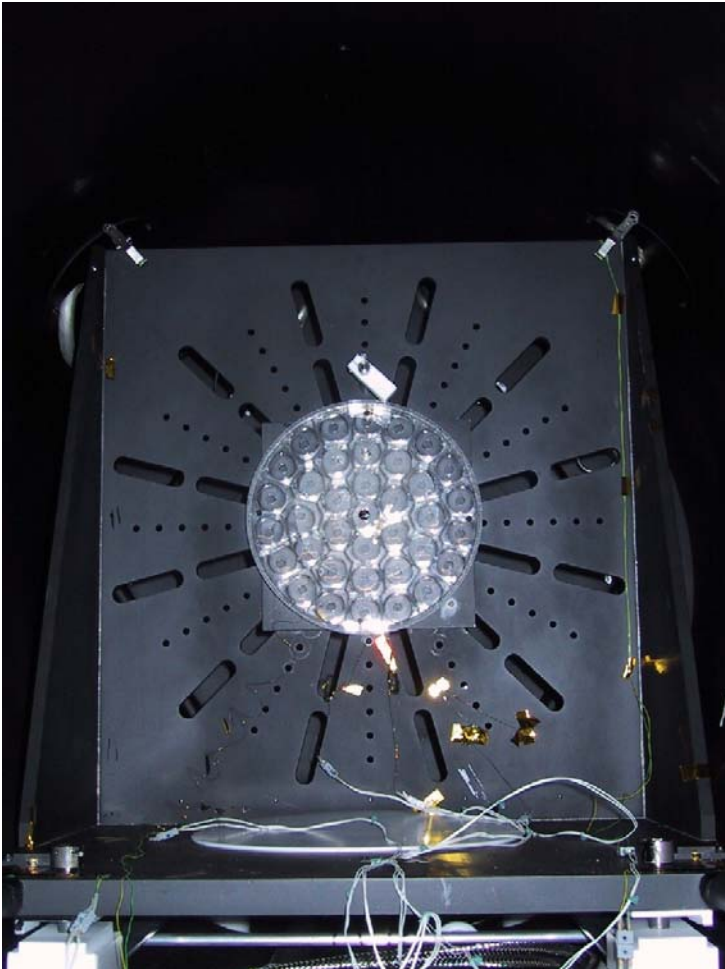
Blank drawing (not final dimensions).

Test Article & Mounting

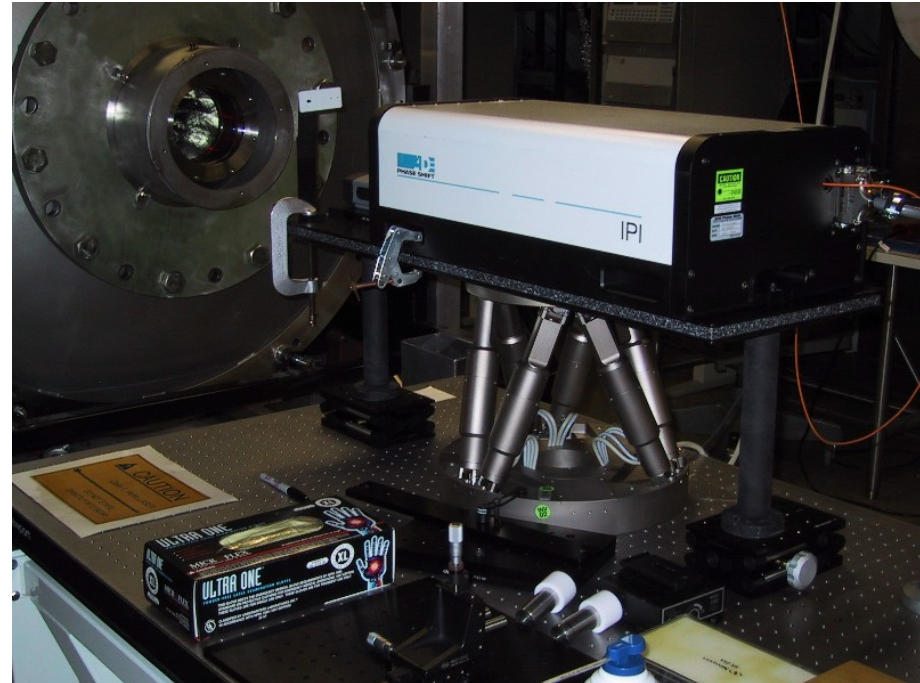


- High-temperature/pressure gas-fused borosilicate sandwich-type mirror:
 - Diameter: 248mm (circular)
 - Radius-of-curvature: 2500mm (R/10)
 - Face-sheet: ~1.5mm thick after grind & polish by MSFC-SOMTC
 - Back-sheet: 3.0mm thick
 - Core structure: 20mm thick, ~43mm diameter cells, 0.5-1.2mm thick walls
 - Areal density: 14kg/m²
 - Fiducials: 4 filled circles (6.5mm Ø) at 90° intervals on 220mm Ø circle.
- Temperature Sensors:
 - 3 silicon temp diodes attached to mirror back using Kapton tape: 1 each near top, center, & bottom (more diodes attached to test stand, shroud, etc).
- Mirror Mounting:
 - Hung on Kapton-wrapped bolt inserted into upper vent hole on mirror back.
 - Mirror bottom rested against two Teflon bolt heads.
 - Teflon safety bumper located in front of mirror top (not touching).
 - Attached to aluminum test stand (with actively cooled base).

Test Set-Up



Mirror installed on test stand
in 1m x 2m chamber.



IPI with F/8 diverger & 1Kx1K CCD atop
Hexapod looking thru 25.4mm thick BK7 window
into chamber (from 1st test). During 2nd test,
ADM mounted atop IPI with two fold mirrors to
align to optical axis.

Test Objectives & Uncertainty



- Test Objectives:
 - *First Test:* Measure surface figure error at ambient (~290K) & cryo (~30K) at least twice for repeatability.
 - *Second Test:* Assess effectiveness of cryo-null figuring and evaluate repeatability of cryo-deformation.
 - *Both Tests:* Measure surface figure error at other temperatures of interest (especially 75K, 55K, & 45K).
 - *Second Test:* Measure RoC at ambient temp/press and change to 30K (-1.35mm expected) using Leica Absolute Distance Meter ($\pm 50\mu\text{m}$).
- Surface Figure Error Measurement Uncertainty:
 - Absolute uncertainty, without subtraction of instrumental error, estimated at $\pm 7\text{nm-rms}$.
 - Uncertainty in any difference between two measurements estimated at only $\pm 3\text{nm-rms}$.
 - Both absolute & difference uncertainties for residual results (FRINGE Zernikes removed) estimated at $\pm 2\text{nm-rms}$.
 - Effects of thermal gradients in mirror and/or differences in such gradients between any two measurements not accounted for in estimates above.

Definitions & Notes



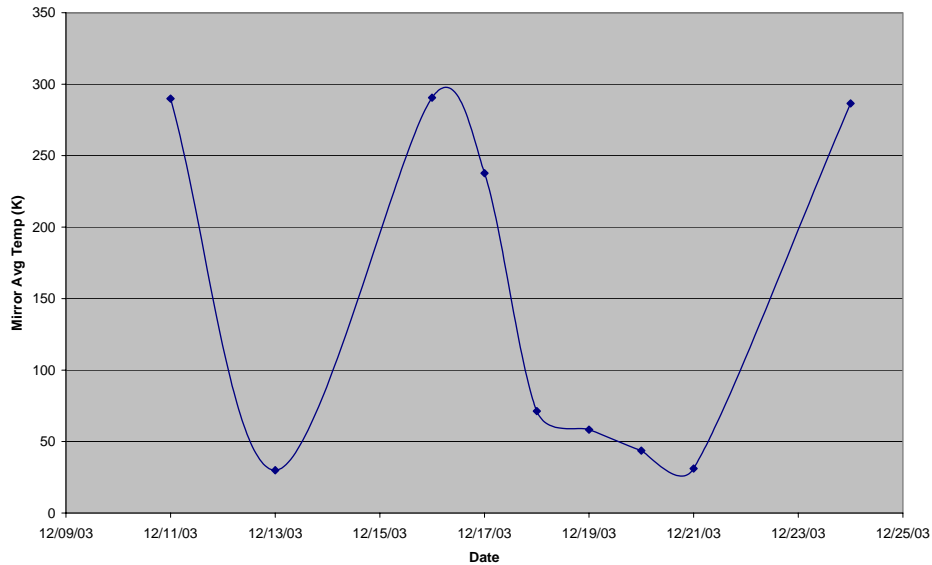
- Three types of maps shown:
 - *Total Figure Error* - surface error map with piston, tilt, & focus removed.
 - *Zernike Fit of Figure Error* – representation of Total Figure Error by fit of all 37 FRINGE Zernike terms.
 - *Residual Figure Error* - surface error map with all 37 FRINGE Zernike terms removed (i.e. Total minus Zernike Fit).
- Each map shown in actual mirror orientation.
- Physical aspects of data:
 - Spatial resolution is 0.341mm/pixel.
 - Average diameter of measured area is 241mm (97.2% of physical diameter).
- ADM requires strong specularly-reflected beam from target:
 - Thus, circular piece of silver-Kapton tape (13mm Ø) applied to center of mirror face during 2nd test to provide adequate reflectance.

Figure & RoC Change vs Temperature

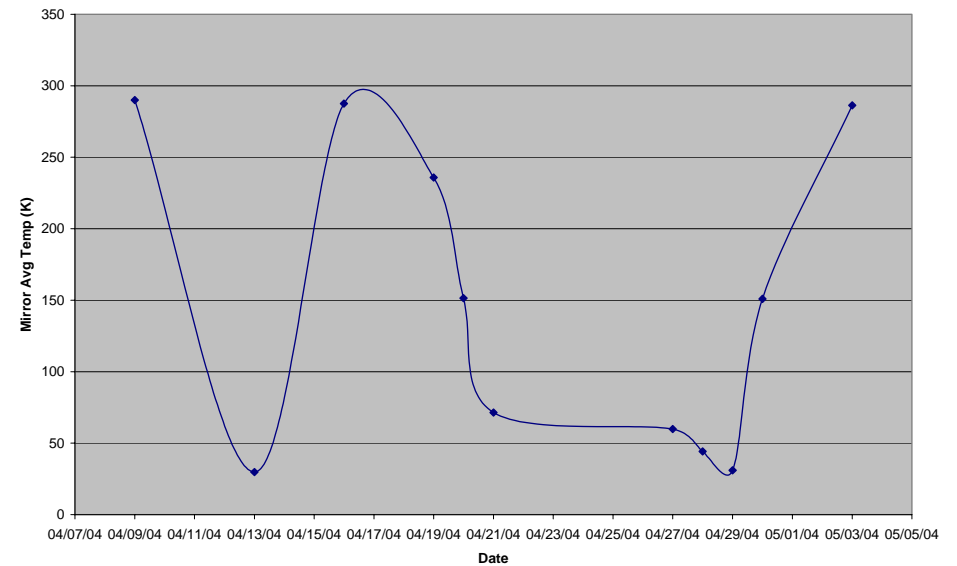
Temperature Timelines



Timeline for 1st Cryo-Test of Hextek 0.25m Mirror



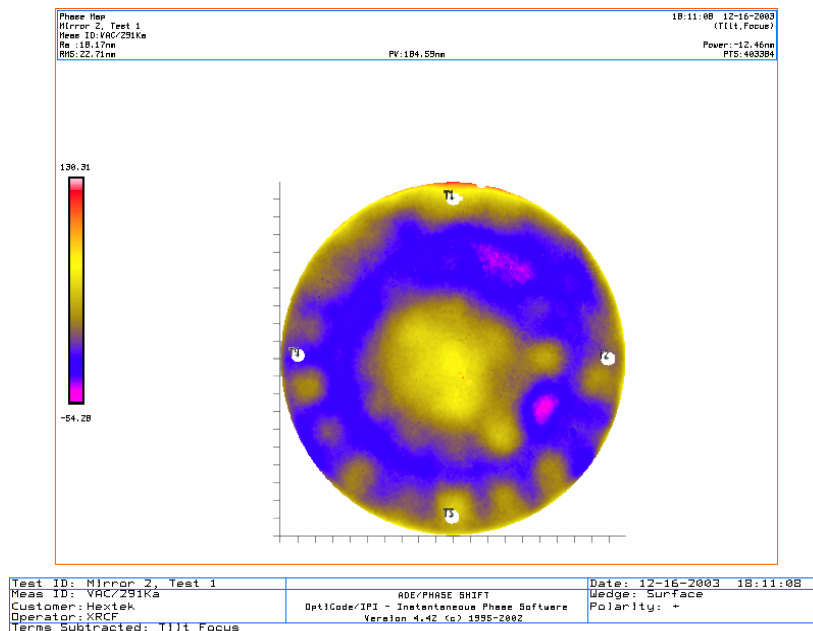
Timeline for 2nd Cryo-Test of Hextek 0.25m Mirror



291K (1st Test, Between Cycles)

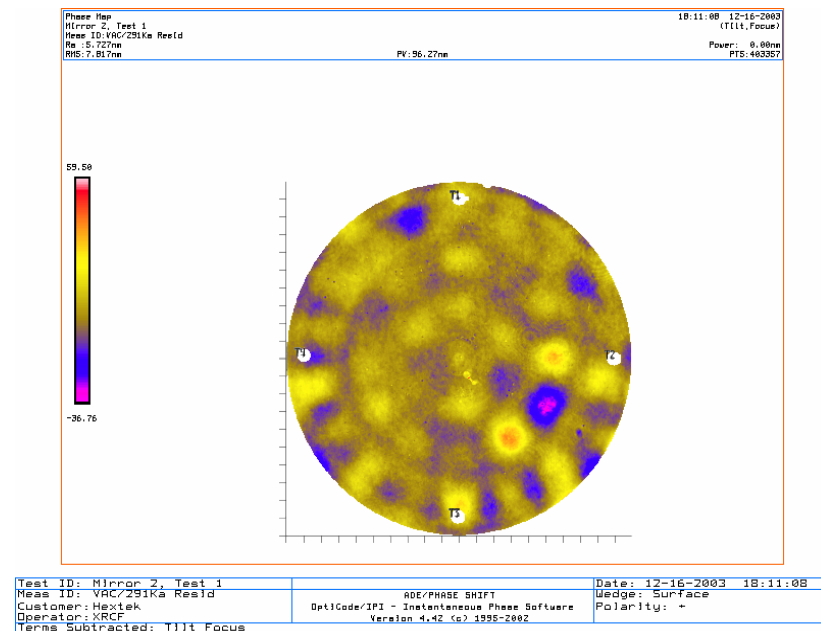


Total Figure Error



PV = 185nm
RMS = 22.7nm

Residual Figure Error



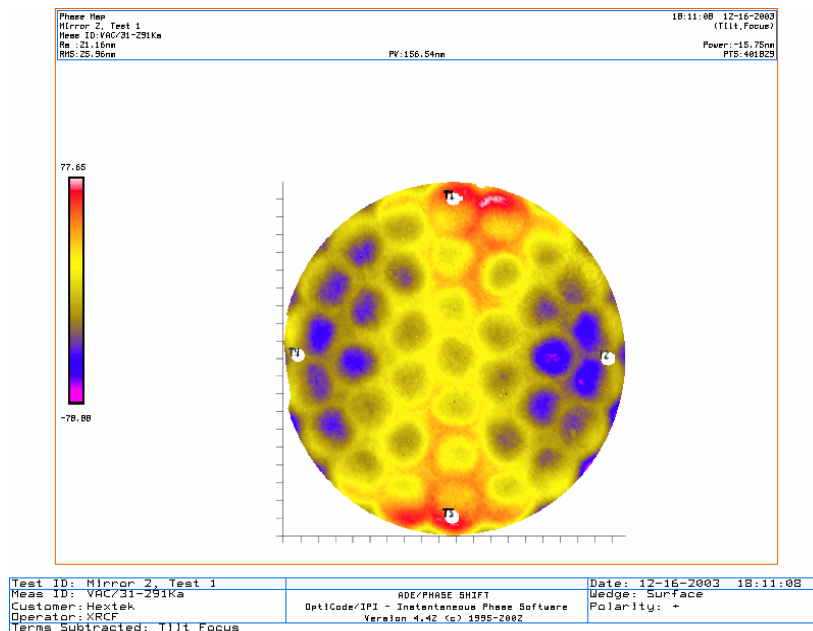
PV = 96nm
RMS = 7.8nm

Repeatable cycle-to-cycle & test-to-test.

Cryo Deformation, 31-291K (1st Test, 2nd Cycle)

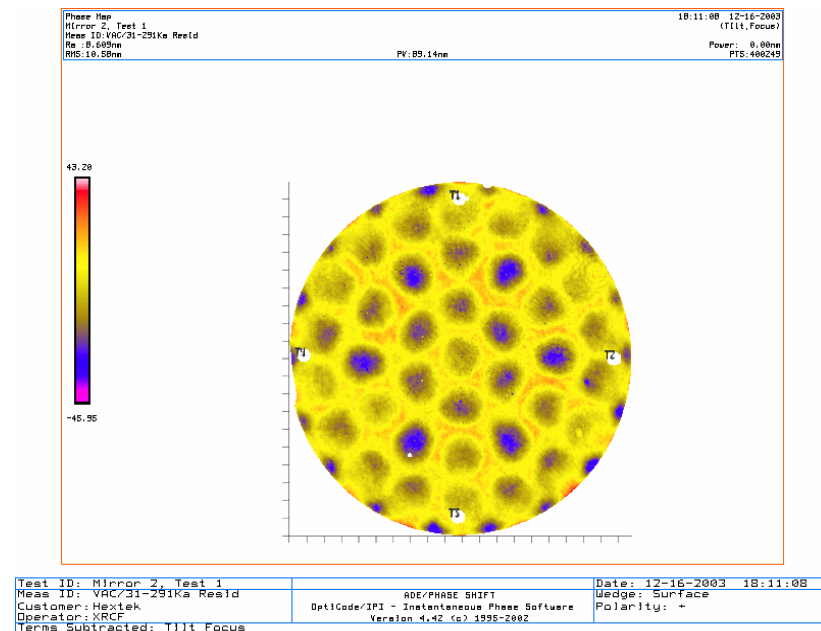


Total Figure Error



PV = 157nm
RMS = 26.0nm

Residual Figure Error



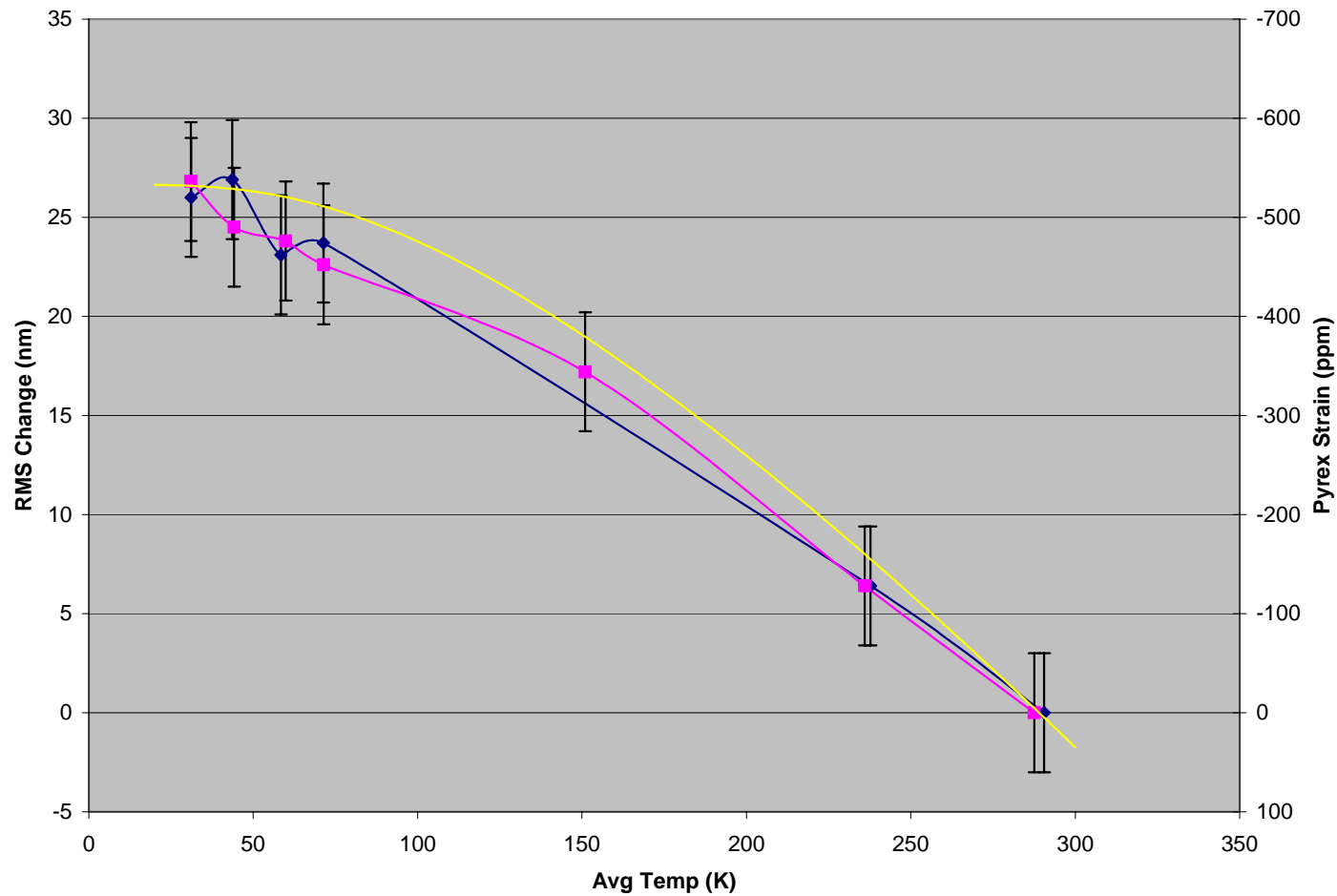
PV = 89nm
RMS = 10.6nm

Repeatable cycle-to-cycle & test-to-test.

RMS Total Figure Change vs Temperature



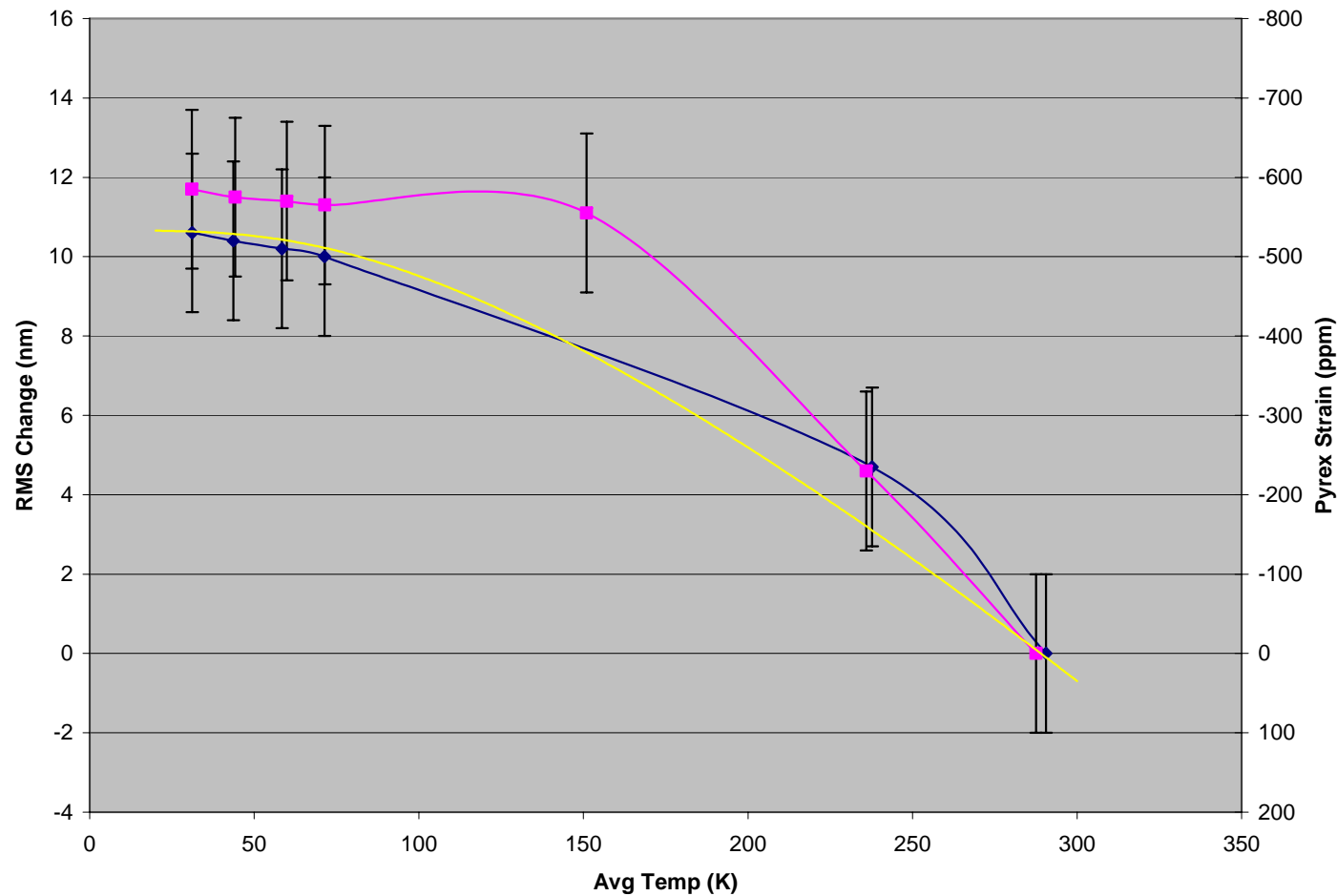
RMS Surface Figure Change vs Temperature for Hextek 0.25m Mirror



RMS Residual Figure Change vs Temperature



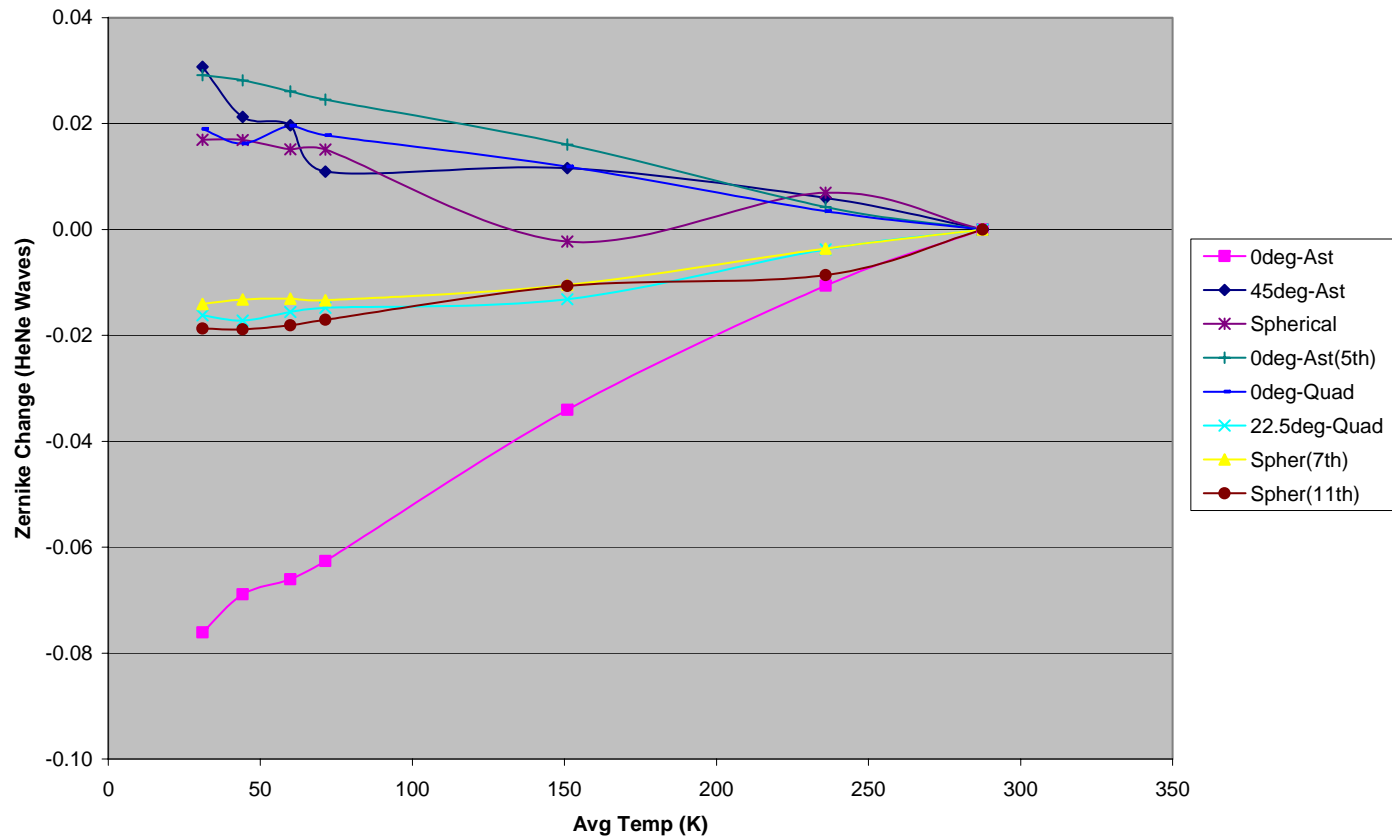
RMS Residual Surface Figure Change vs Temperature for Hextek 0.25m Mirror



Zernike Change vs Temperature (2nd Test)



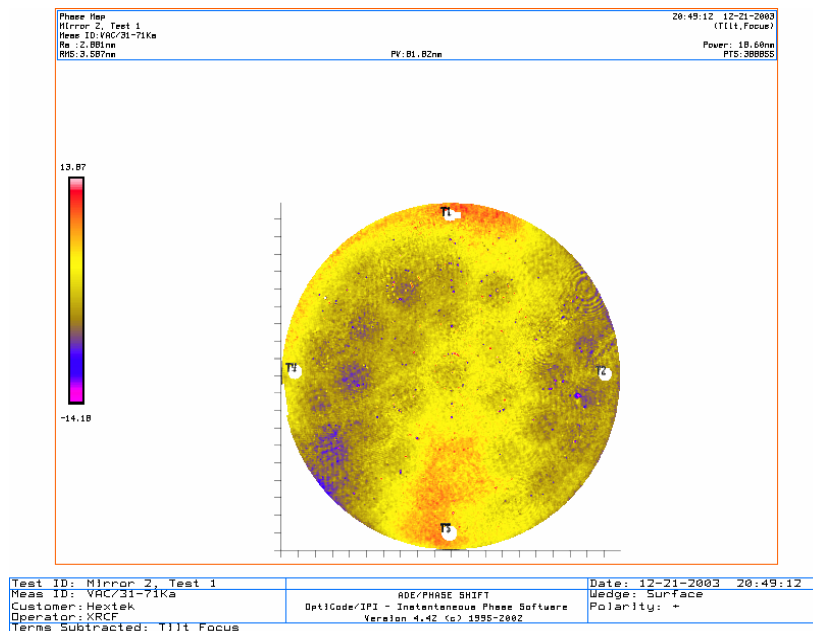
Zernike Change vs Temperature for Hextek 0.25m Mirror (Test 2, Cycle 2)



Cryo Deformation, 31-71K (1st Test, 2nd Cycle)

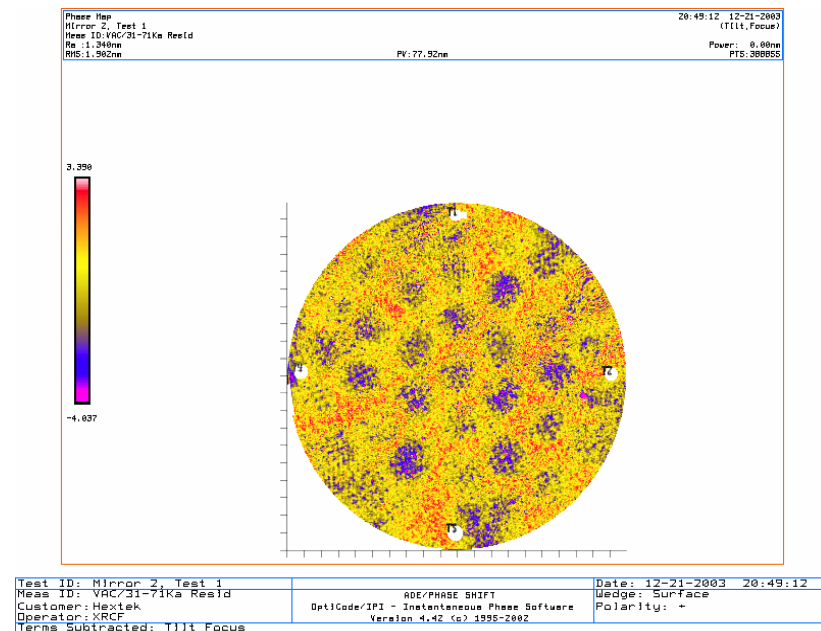


Total Figure Error



PV = 28nm
RMS = 3.6nm

Residual Figure Error



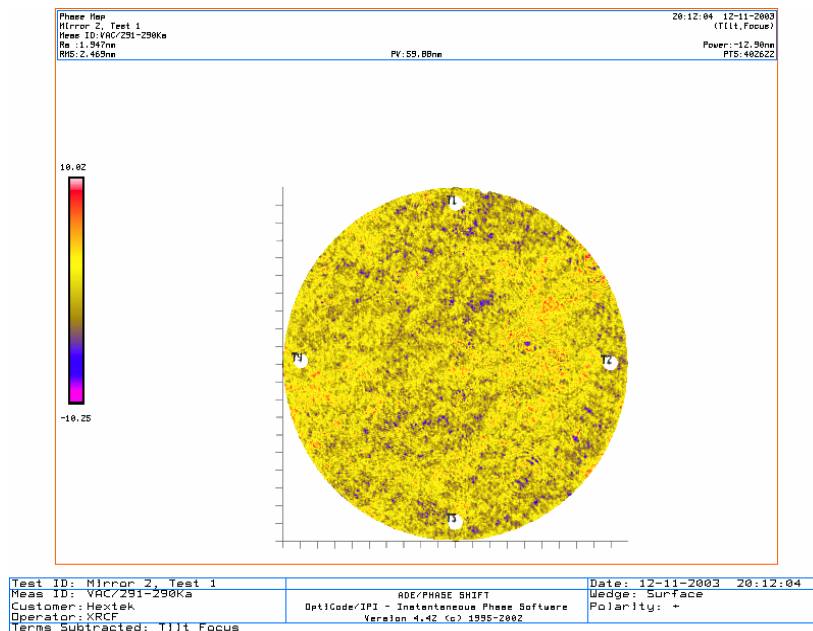
PV = 8nm
RMS = 1.9nm

Repeatable test-to-test.

Post minus Pre-Cryo Ambient Change, 291-290K (1st Test, 1st Cycle)

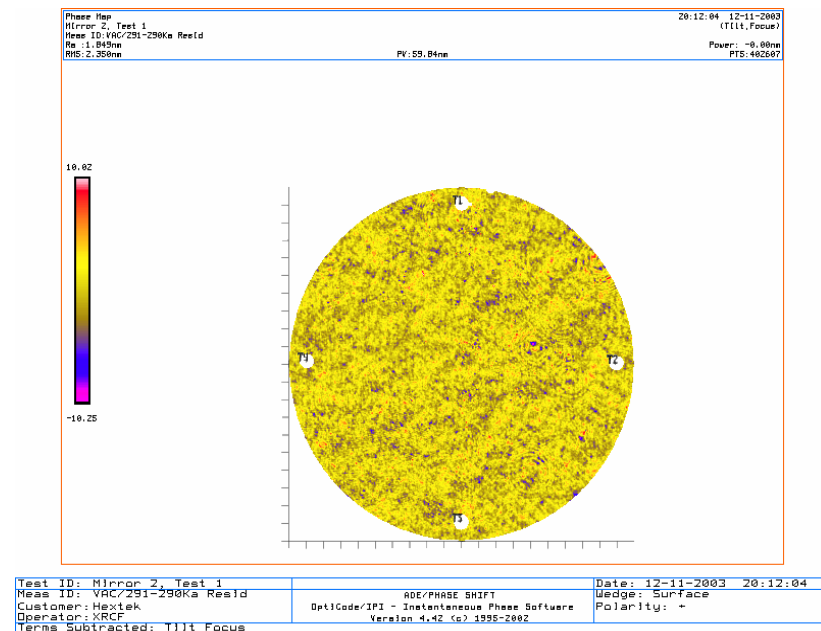


Total Figure Error



PV = 20nm
RMS = 2.5nm

Residual Figure Error



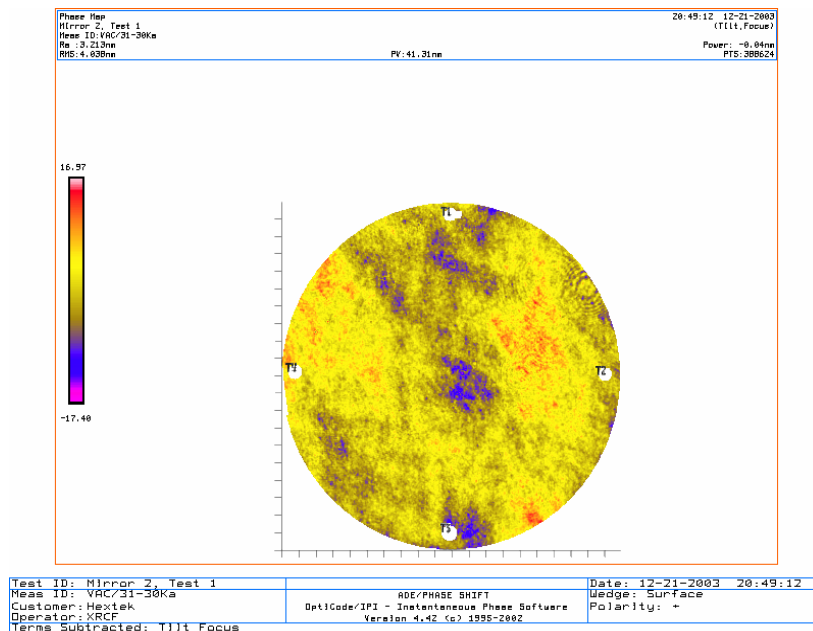
PV = 20nm
RMS = 2.4nm

Repeatable cycle-to-cycle & test-to-test.

2nd minus 1st 30K, 31-30K (1st Test)

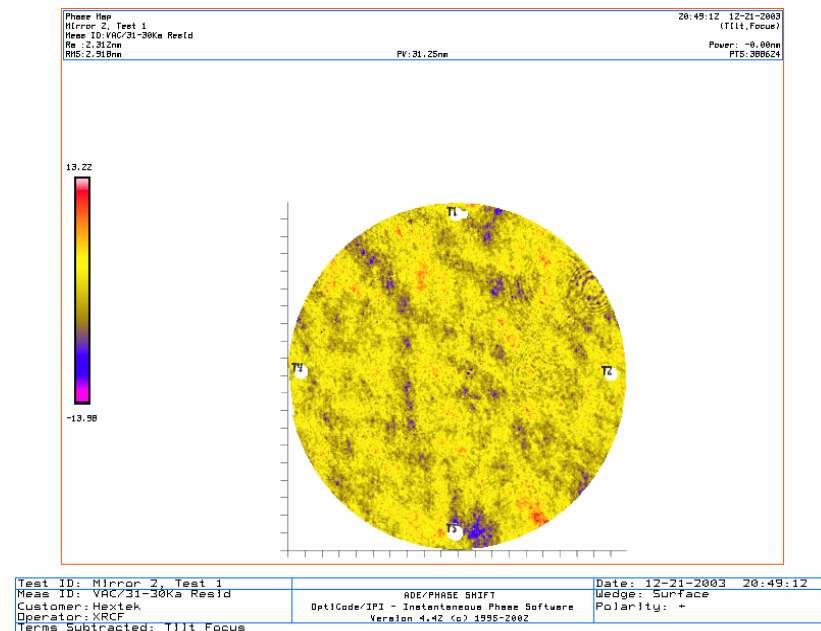


Total Figure Error



PV = 34nm
RMS = 4.0nm

Residual Figure Error



PV = 26nm
RMS = 2.9nm

Repeatable test-to-test.

Absolute RoC at 290K

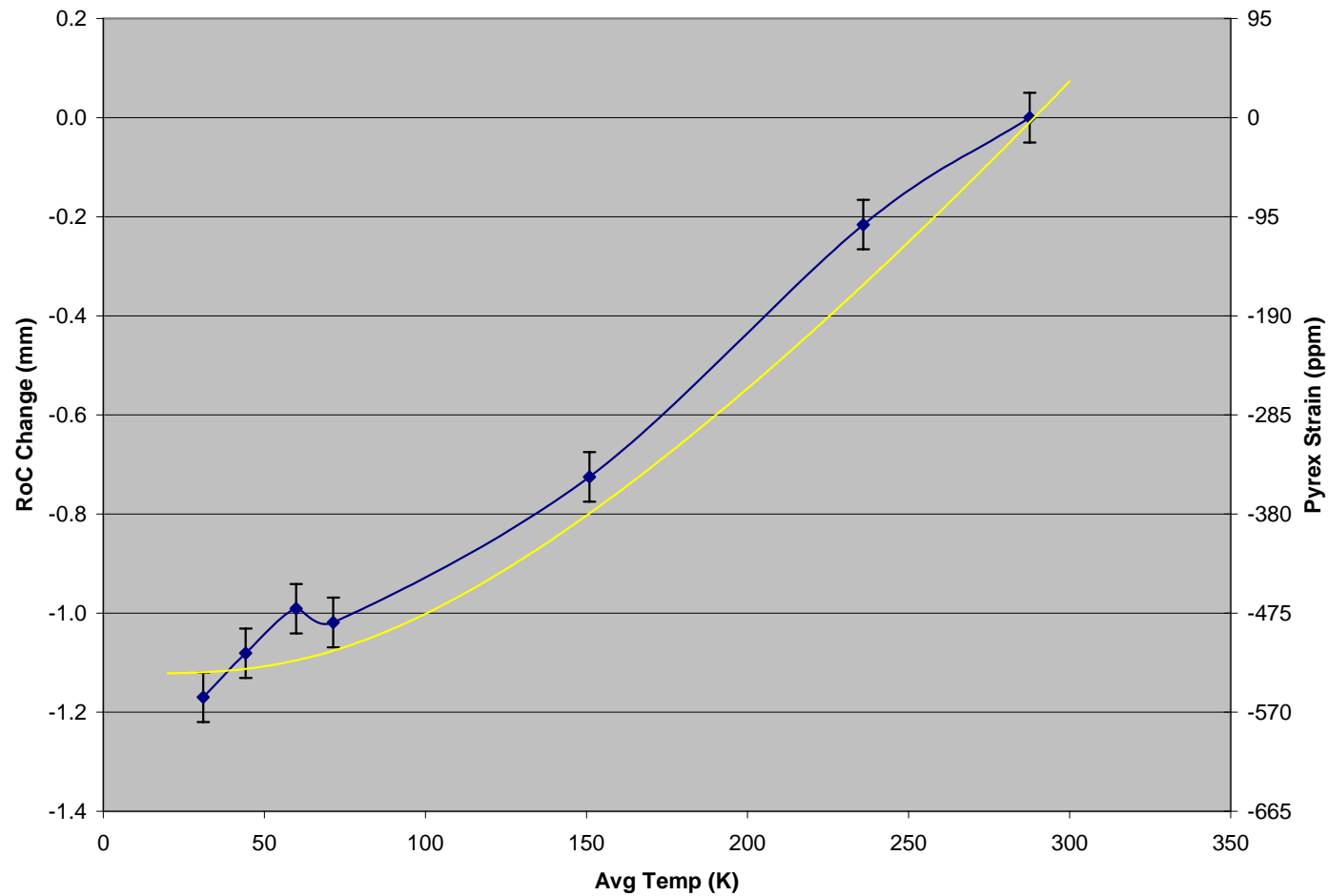


- Measured absolute RoC at 290K during 2nd test.
 - ADM moved to tripod behind IPI optical table (to make distance to IPI focus >1.5m min measurable distance).
 - Installed small flat mirror at IPI focus for measurement to mirror center-of-curvature.
 - Ambient pressure.
 - Chamber dome (i.e. window) removed from ADM path.
- RoC results from two distance measurements.
 - Aligned IPI to mirror, nulled focus, aligned ADM to IPI/mirror, then measured distance #1.
 - Inserted flat mirror at IPI focus, aligned mirror to IPI (cats-eye), nulled focus, tweaked alignment of mirror to ADM, then measured distance #2.
 - **RoC(290K) = D1 – D2 = 2505.016 ± 0.050mm**

RoC Change vs Temperature (2nd Test)



RoC Change vs Temperature for Hextek 0.25m Mirror (Test 2, Cycle 2)



Summary of Figure & RoC Change vs Temperature



- Total figure change (26nm-rms) near linear vs temp and dominated by 0° astigmatism.
- Residual figure change (11nm-rms) closer to borosilicate strain curve, and shows obvious quilting of core structure.
- Total figure change within 30K to 70K range small (4nm-rms), but real, and dominated by 0° astigmatism.
- Residual figure change within 30K to 70K range even smaller (2nm-rms), but also real, with slight change in quilting.
- Figure at ambient (~290K) very repeatable (<3nm-rms). So, no change in ambient figure due to cryo-cycling.
- Figure at cryo (~30K) repeatable (<4nm-rms).
- Cryo-deformation between 290K & 30K very repeatable.
- RoC change (-1.17mm) near linear vs temp and differs from expected value (-1.35mm) by only +0.18mm (+13%).
- RoC very repeatable at ambient & cryo.

Effectiveness of Cryo-Null Figuring

Goal of Cryo-Null Figuring

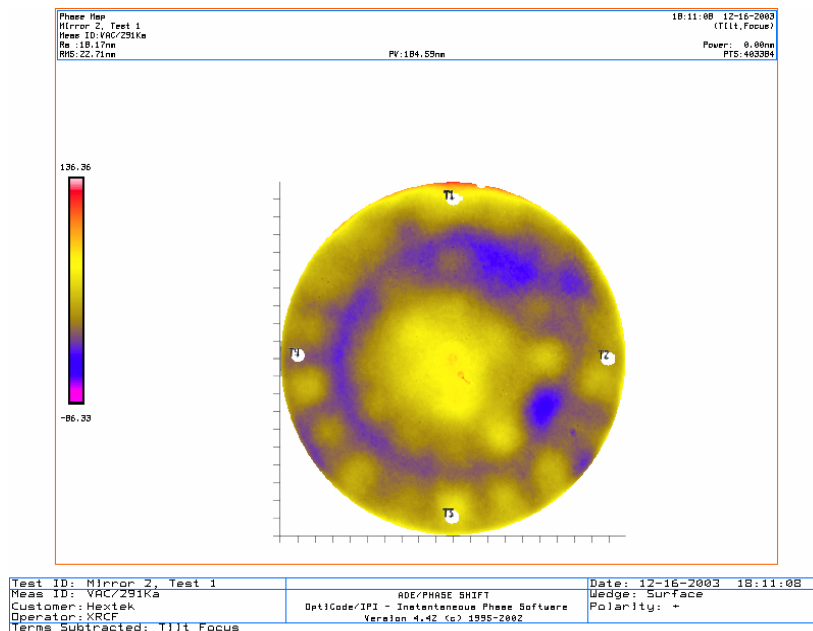


- Mirror cryo-null figured by QED using 30K-290K change from 1st cryo test as hit map.
- Thus, if perfectly cryo-null figured, figure at 30K would now be exactly same as that seen at 290K during 1st cryo test.

Visual Check of Cryo-Null Figuring Efficiency: [291K, 1st Test] & [31K, 2nd Test] (should be same)

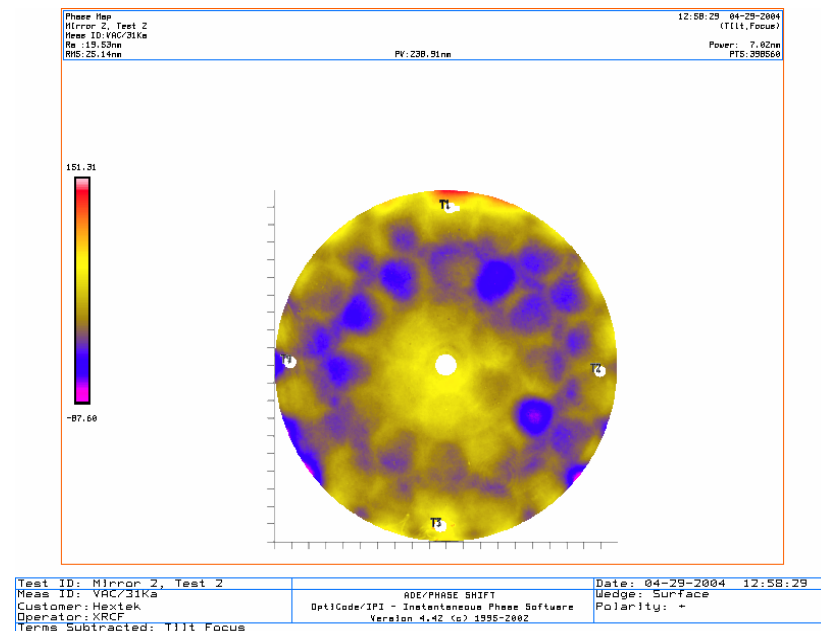


**Total Figure Error at
291K From 1st Cryo Test**



**PV = 157nm
RMS = 22.7nm**

**Total Figure Error at
31K From 2nd Cryo Test**



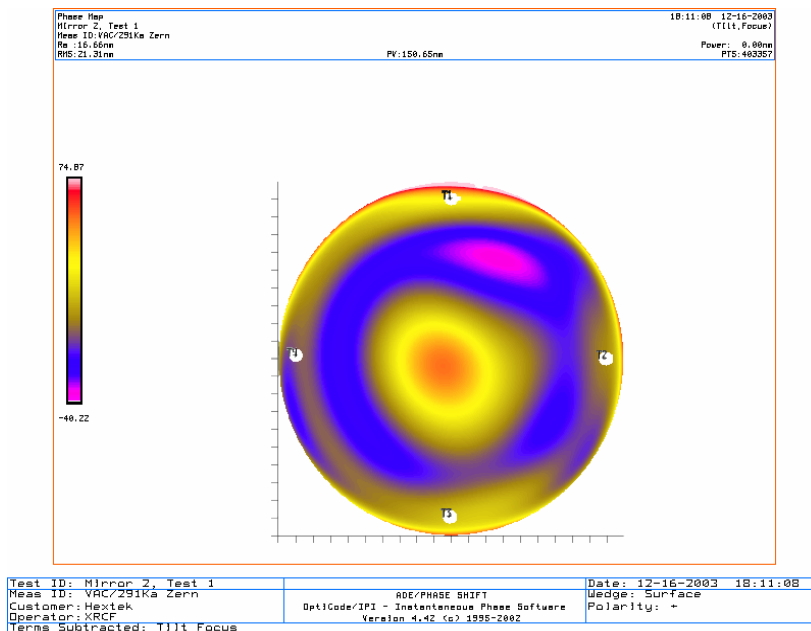
**PV = 210nm
RMS = 25.1nm**

Low-order match looks good, but appears that 31K, 2nd Test has more quilting.

Visual Check of Cryo-Null Figuring Efficiency: [291K, 1st Test] & [31K, 2nd Test] (should be same)

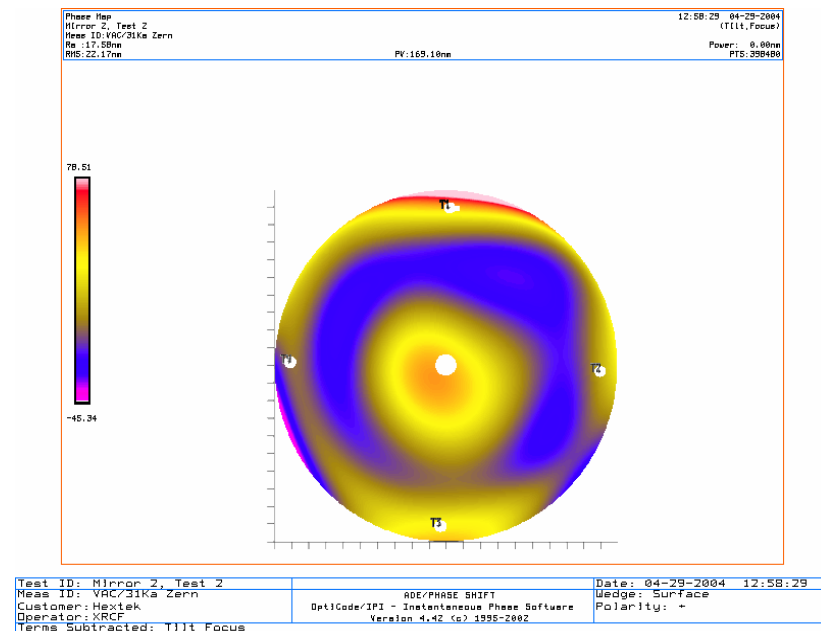


**Zernike Fit of Figure Error at
291K From 1st Cryo Test**



**PV = 115nm
RMS = 21.3nm**

**Zernike Fit of Figure Error at
31K From 2nd Cryo Test**



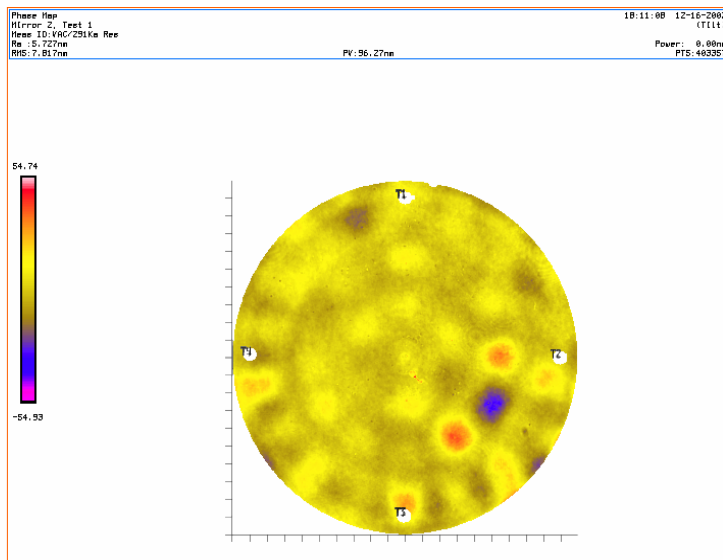
**PV = 124nm
RMS = 22.2nm**

Confirms that low-order match looks pretty good visually.

Visual Check of Cryo-Null Figuring Efficiency: [291K, 1st Test] & [31K, 2nd Test] (should be same)



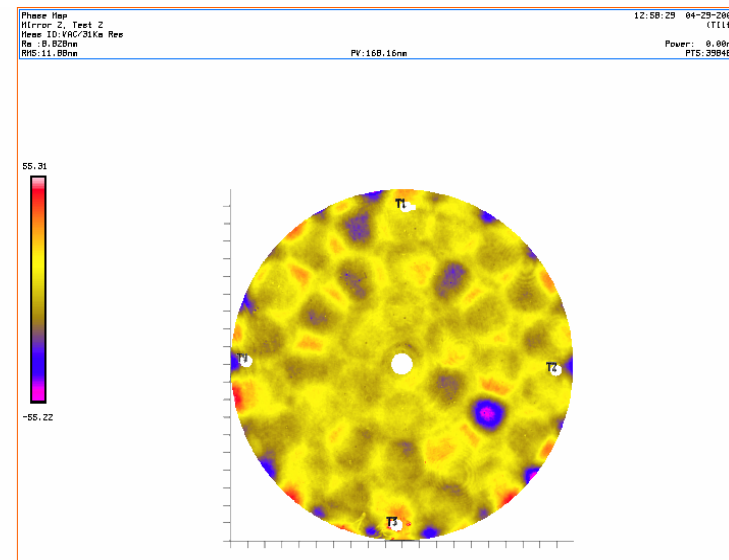
**Residual Figure Error at
291K From 1st Cryo Test**



Test ID: Mirror 2, Test 1	Date: 12-16-2003 18:11:08
Meas ID: VAC/291Ka Res	Wedge: Surface
Customer: Hextek	Polarity: +
Operator: XRCF	Version 4.42 (c) 1995-2002
Terms Subtracted: Tilt	

**PV = 110nm
RMS = 7.8nm**

**Residual Figure Error at
31K From 2nd Cryo Test**



Test ID: Mirror 2, Test 2	Date: 04-29-2004 12:58:29
Meas ID: VAC/31Ka Res	Wedge: Surface
Customer: Hextek	Polarity: +
Operator: XRCF	Version 4.42 (c) 1995-2002
Terms Subtracted: Tilt	

**PV = 105nm
RMS = 11.9nm**

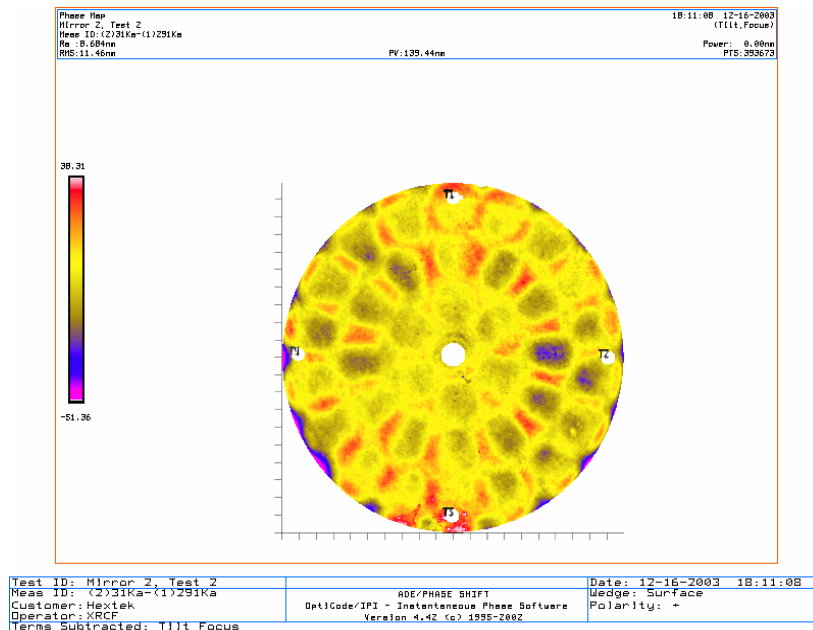
Confirms that 31K, 2nd Test has more quitting than target surface.

Quantitative Check of Cryo-Null Figuring Efficiency: [31K, 2nd Test] minus [291K, 1st Test] (should be zero)

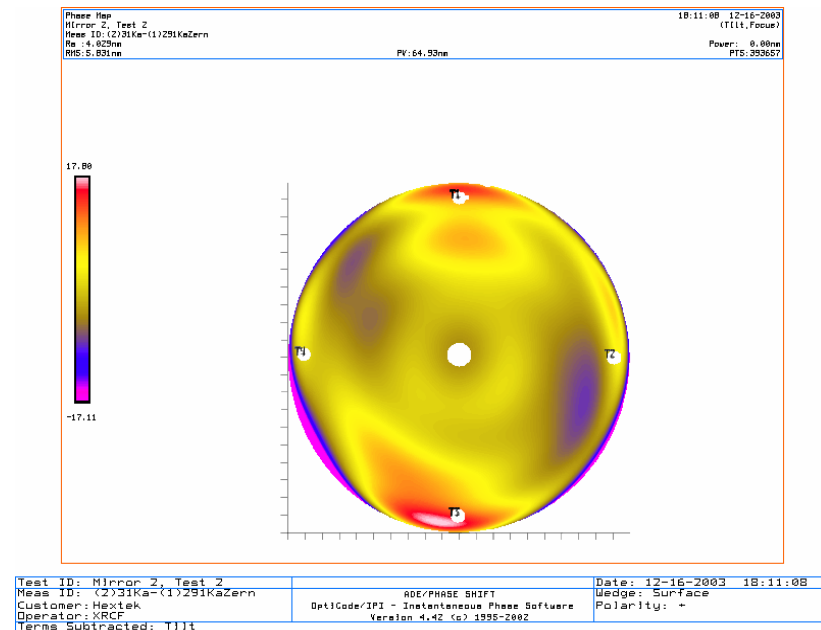


Total Figure Error

Zernike Fit of Figure Error



PV = 90nm
RMS = 11.5nm



PV = 38nm
RMS = 5.8nm

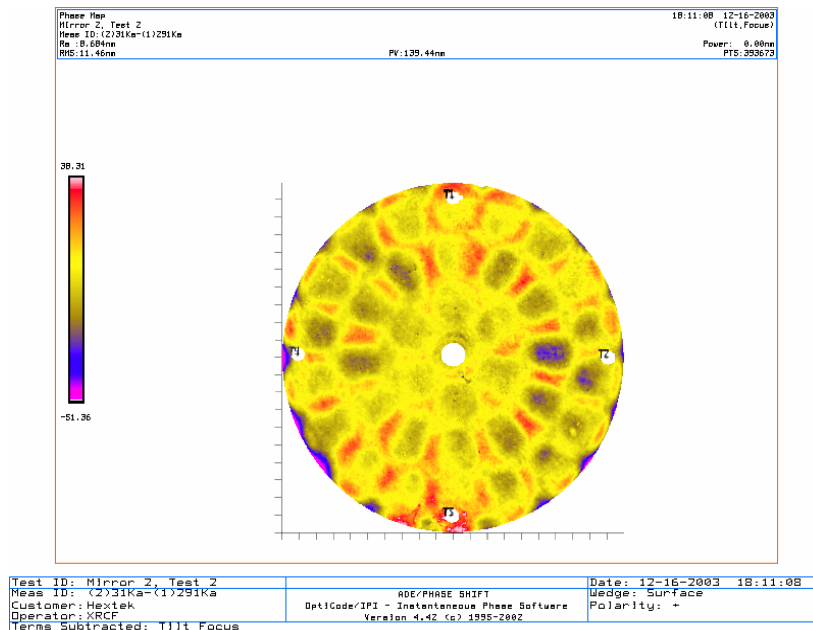
Zernike fit of difference shows only 5.8nm-rms of remaining low-order error.

Quantitative Check of Cryo-Null Figuring Efficiency: [31K, 2nd Test] minus [291K, 1st Test] (should be zero)

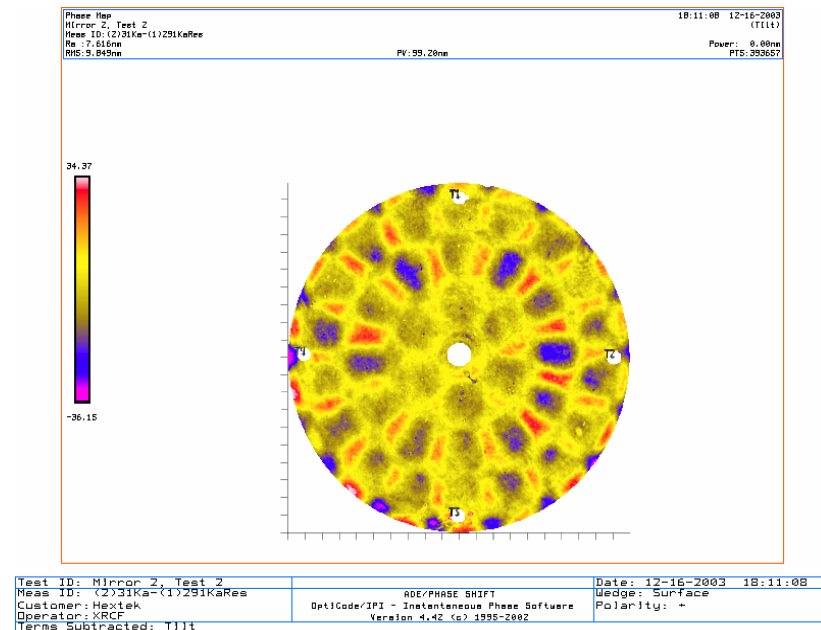


Total Figure Error

Residual Figure Error



PV = 90nm
RMS = 11.5nm



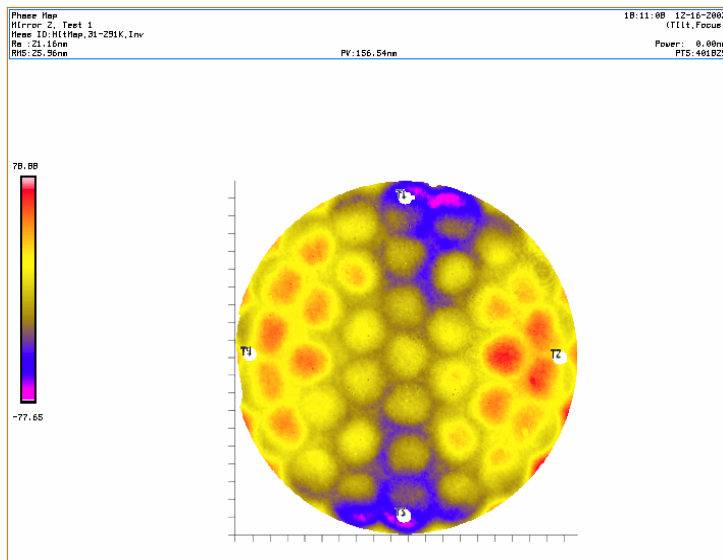
PV = 71nm
RMS = 9.9nm

Confirms that cryo-null figuring error dominated by high-order, or quilting, error
- will be explained by a misregistration error.

Visual Check of *Desired* vs *Actual* Surface Change Due to Cryo-Null Figuring:



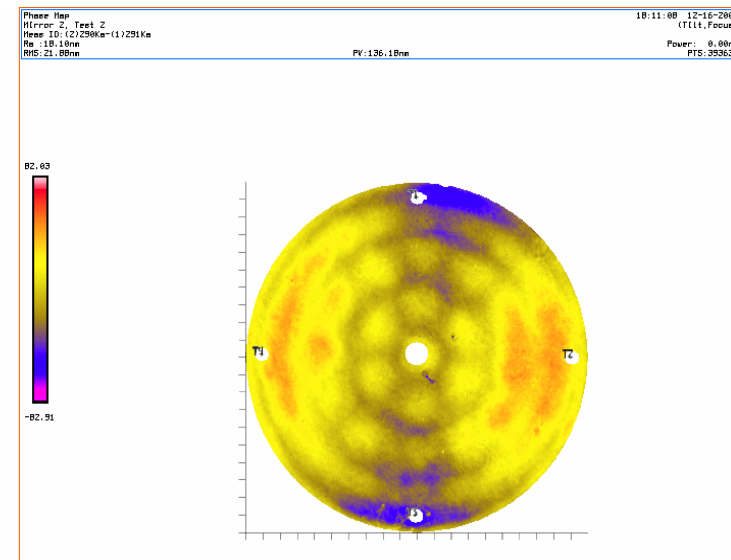
**Total Desired Fig Chg
[291K(1) – 31K(1)]**



Test ID: Mirror 2, Test 1	Date: 12-16-2003 18:11:08
Meas ID: H1Map, 31-291K, Inv	Wedge: Surface
Customer: Hextek	Polarity: +
Operator: XRCF	OptiCode/IP1 - Instantaneous Phase Software
Terms Subtracted: Tilt Focus	Version 4.42 (c) 1995-2002

**PV = 157nm
RMS = 26.0nm**

**Total Actual Fig Chg
[290K(2) – 291K(1)]**



Test ID: Mirror 2, Test 2	Date: 12-16-2003 18:11:08
Meas ID: (2)290Ka-(1)291Ka	Wedge: Surface
Customer: Hextek	Polarity: +
Operator: XRCF	OptiCode/IP1 - Instantaneous Phase Software
Terms Subtracted: Tilt Focus	Version 4.42 (c) 1995-2002

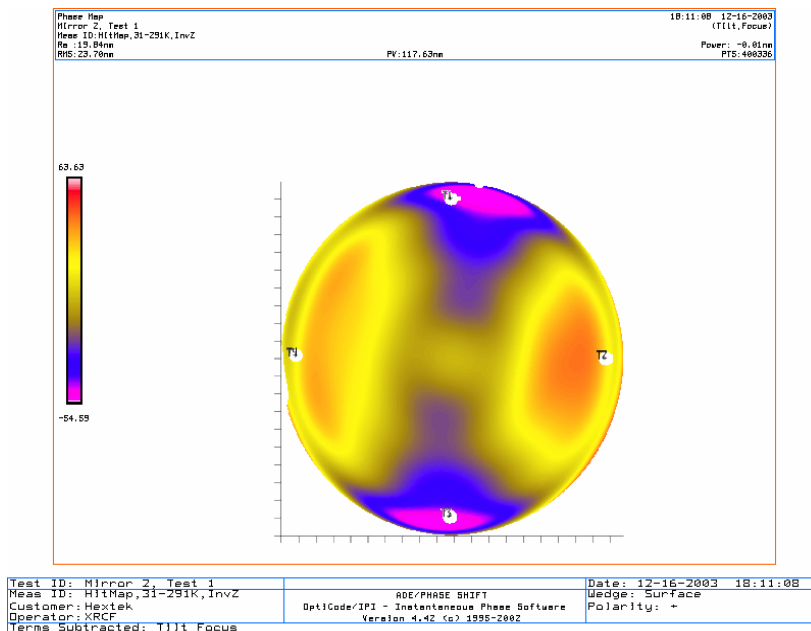
**PV = 117nm
RMS = 21.9nm**

As before, low-order correction is good – total error dominated by high-order error.

Visual Check of *Desired vs Actual* Surface Change Due to Cryo-Null Figuring:

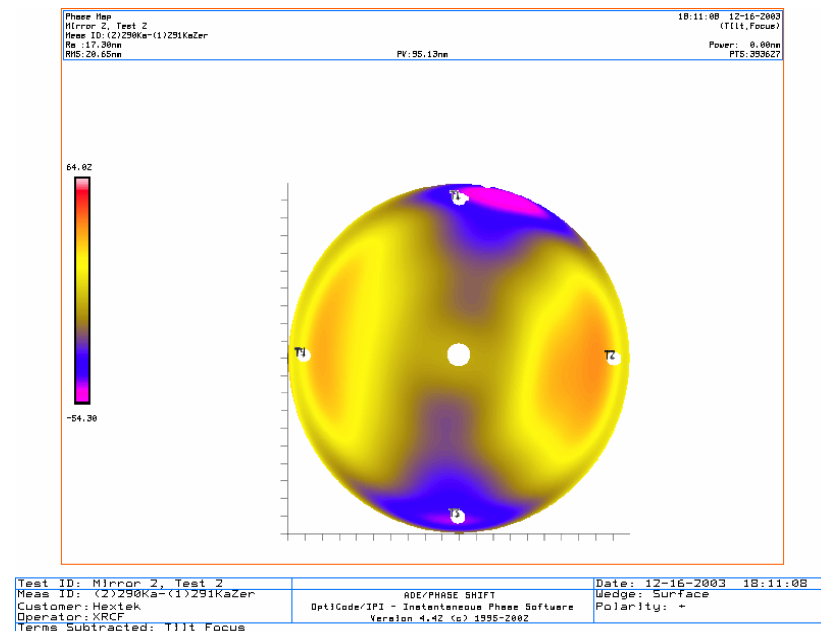


**Zernike Fit of Desired Fig Chg
[291K(1) – 31K(1)]**



**PV = 106nm
RMS = 23.7nm**

**Zernike Fit of Actual Fig Chg
[290K(2) – 291K(1)]**



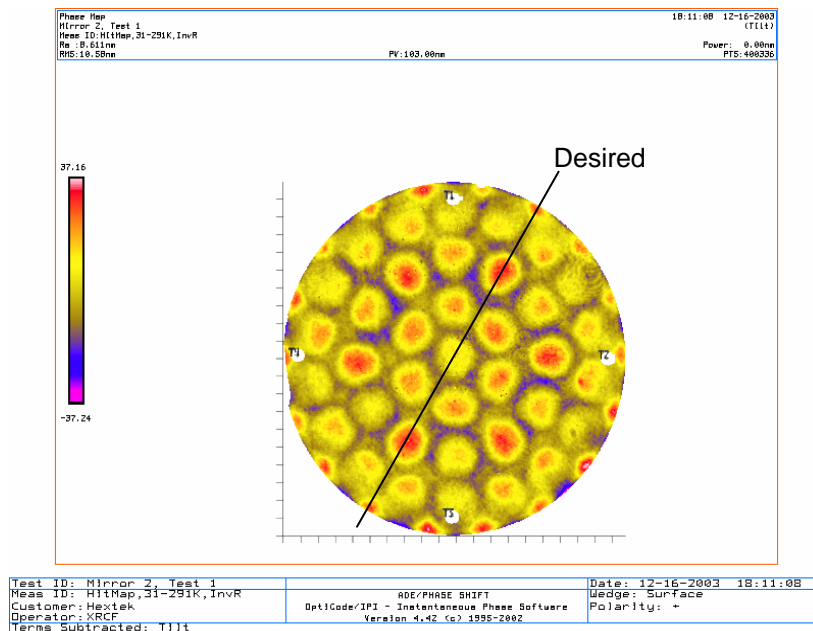
**PV = 95nm
RMS = 20.7nm**

Confirms good low-order match.

Visual Check of *Desired* vs *Actual* Surface Change Due to Cryo-Null Figuring:

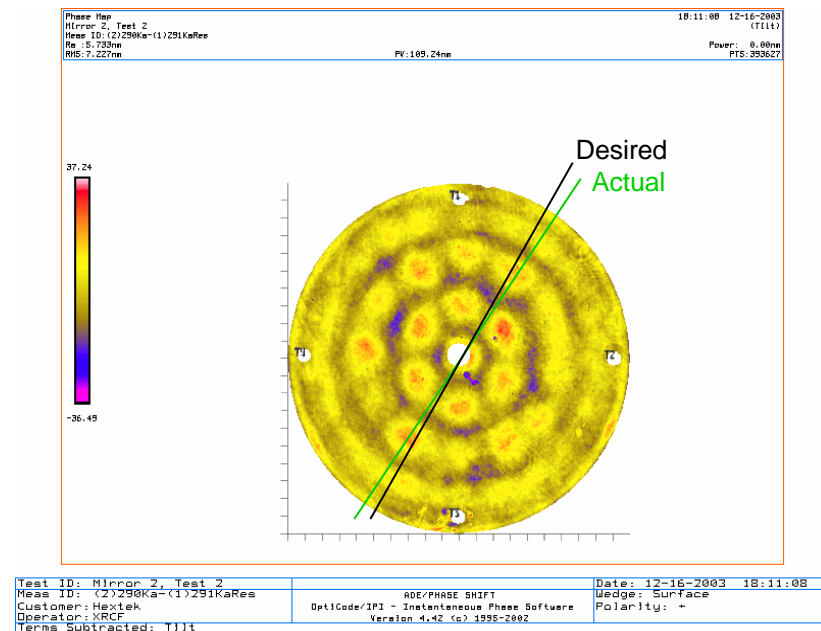


**Residual Desired Fig Chg
[291K(1) – 31K(1)]**



**PV = 65nm
RMS = 10.6nm**

**Residual Actual Fig Chg
[290K(2) – 291K(1)]**



**PV = 55nm
RMS = 7.2nm**

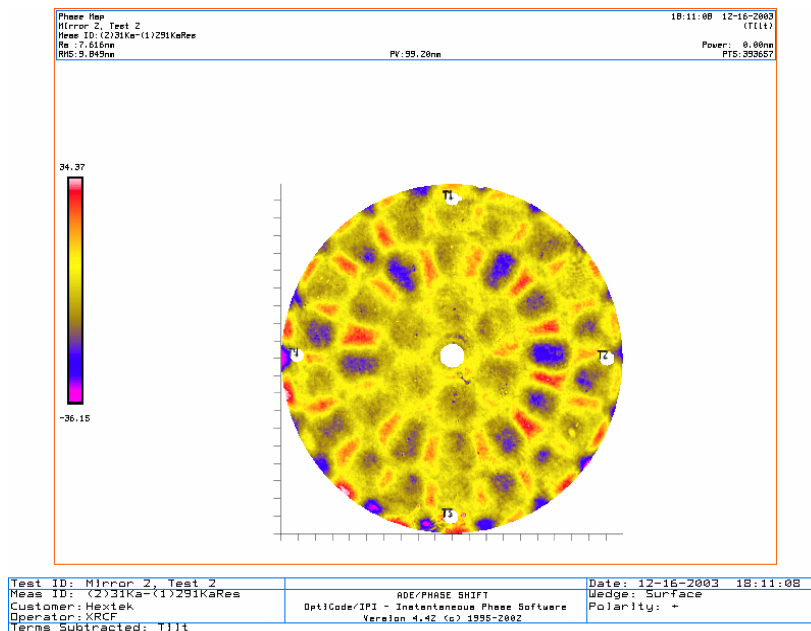
From these plots, appears cryo-null figuring hit-map was slightly misregistered to part in clocking by ~5° CW (confirmed via overlay of hardcopies).

Simulation of Clocking Error in Cryo-Null Figuring Hit-Map: [31-291K(1)] – [31-291K(1), 5.3°CW]

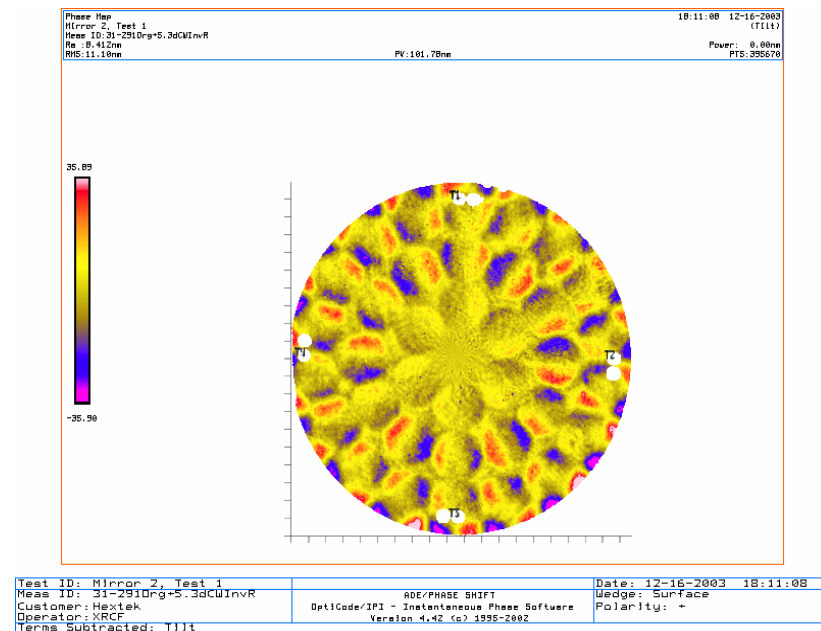


***Measured* Residual Figure Error**

***Simulated* Residual Figure Error**



**PV = 71nm
RMS = 9.9nm**



**PV = 89nm
RMS = 11.1nm**

- 31K(2)–291K(1) result, on left, compares well in both magnitude & form (compare shading) to simulated result, on right, giving strong evidence of clocking error.
- Good agreement also indicates MRF performed well aside from clocking error.

Cryo-Null Figuring Summary



- *Cryo-null figuring good to about 12nm-rms (cryo fig error reduced by 56%). Low-frequency error corrected well, to 6nm-rms (reduced by 76%). High-frequency, or cryo-quilting, error corrected to only 10nm-rms (reduced by only 7%) because of misregistration.*
- Looking at new (290K, 2nd Test) minus old (291K, 1st Test) figure at ambient (i.e. figure change imparted by cryo-null figuring), *appears cryo-null figuring hit-map was slightly misregistered to part in clocking by about 5° CW.*
- Effects of 5° rotational shear analyzed using cryo-deformation from 1st Test. Results match observed high-frequency error.
- Know that fiducials were replaced on mirror face at MSFC after cryo-null figuring in repeatable manner by examining template & method used, and since 30K-290K maps from 1st & 2nd tests match.
- Part alignment during polishing was also reviewed and appeared to be more than adequate. Not yet clear where misregistration occurred.
- Also looked at effects of flipping hit-map left/right & top/bottom, but results quite different from observed error.
- Bottom line: 56% reduction in cryo figure error with 1 hour of MRF polishing time – results likely even better with correct hit-map orientation.